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An Indirect Search for WIMPs with Super-Kamiokande

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Abstract. A potential source of high energy neutrinos is the annihilation of Weakly Interacting Massive Particles (WIMPs) collecting in gravitational potential wells such as the centers of the Earth, the Sun, or the Galaxy. A search for such a WIMP annihilation signal using the Super-Kamiokande (Super-K) detector is presented. Super-K observes 1.1 upward through-going muons per day. These events are caused by high energy (typical $E_\nu \sim 100$ GeV) ν_μ interactions in the rock under the detector, and are generally consistent with the expected flux from atmospheric neutrinos. No enhancement of the neutrino signal due to WIMP annihilation is seen, so upper limits on the possible flux of WIMPS are set. These limits are compared to those from other such indirect searches, and a model-independent method is used to compare the Super-K results with direct-detection WIMP experiments.

1 Introduction

There is growing evidence indicating that non-baryonic cold dark matter constitutes a major component of the universe's total mass, seen only via its gravitational influences (Spergel, 1997). Current models of the Universe (Turner, 2000) suggest that it accounts for (30 ± 7)% of the closure density of the universe.

Weakly Interacting Massive Particles (WIMPs) are a promising cold dark matter candidate (Jungman *et al.*, 1996). WIMPs, stable particles which arise in extensions of the standard model, undergo only weak-scale interactions with matter but have masses ranging from tens of GeV to a few TeV. If WIMPs exist, their relic abundance (governed by electroweak scale interactions) is remarkably close to the inferred density of dark matter in the universe (Jungman *et al.*, 1996). The lightest supersymmetric particle (LSP) of supersymmetric theories is a theoretically well developed WIMP candidate (Jungman *et al.*, 1996). If R-parity is conserved, the LSP is stable and hence should be present in the Universe as a cosmological relic from the Big Bang. A likely candidate for this LSP is the neutralino (Ellis *et al.*, 1984). Current LEP data and cosmological constraints impose a lower limit of about 51 GeV and an upper limit of 600 GeV on the neutralino mass (Ellis *et al.*, 2000).

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In this paper we describe an indirect method to search for such relic WIMPS using the Super–Kamiokande detector to look for a high energy neutrino signal resulting from WIMP annihilation in the Earth, the Sun, and the Galactic Center. This is in contrast to direct-detection experiments which look for signatures of WIMP interactions with a nucleus in a low background detector. However, both direct and indirect detection experiments probe the coupling of WIMPs to nuclei, allowing a comparison of our results with those of direct-detection of dark matter experiments.

2 Indirect WIMP Searches using Neutrino-Induced Muons

If WIMPs are indeed the dark matter composing our galactic halo they will accumulate in the Sun and Earth. When their orbits pass though a celestial body the WIMPs have a small but finite probability of elastically scattering with a nucleus. If the resulting velocity after such scattering is less than the escape velocity, they become gravitationally trapped and eventually settle into the core of that body.

WIMPs which have accumulated in this way annihilate into τ leptons, b, c and t quarks, gauge bosons, and Higgs bosons. Over time, equilibrium is achieved between capture and annihilation, making the annihilation rate half of the capture rate. High energy ν_μ are produced by the decay of the annihilation products. The expected neutrino fluxes from the capture and annihilation of WIMPs in the Sun and Earth depend upon the composition and escape velocity of the celestial body, the flux of WIMPS, and the the WIMP-nucleon scattering cross-section. There are many calculations of expected neutrino fluxes from WIMP capture and annihilation in the Sun and Earth (Press & Spergel, 1985; Freese, 1986; Silk *et al.*, 1985; Krauss *et al.*, 1986; Gaisser *et al.*, 1986).

Recently it has also been noticed that if cold dark matter is present at the Galactic Center it can be accreted by the central black hole into a dense spike in the density distribution (Gondolo & Silk, 1999). WIMP annihilations in this region could make it a compact source of high energy neutrinos.

The energetic ν_μ resulting from WIMP annihilation could be detected in neutrino detectors. The mean neutrino energy ranges from 1/3 to 1/2 the mass of the WIMP, and the neutrinos can undergo charged current interactions with the rock around the detector to produce muons. Thus, neutrino-induced muons coming from the direction of the Sun, the Earth and the Galactic Center could provide a signature of non-baryonic cold dark matter.

3 WIMP Searches in Super–K

The Super–Kamiokande ("Super–K") detector is a 50,000 tonne water Cherenkov detector, located in the Kamioka-Mozumi mine in Japan with 1000 m rock overburden. It is divided by a lightproof barrier into an inner detector with 11,146 inward-facing 50 cm Hamamatsu Photomultiplier Tubes (PMTs) and an outer detector equipped with 1,885 outward-facing 20 cm Hamamatsu PMTs serving as a cosmic ray veto counter (Y. Fukuda *et al.*, 1998).

Interactions of atmospheric ν_μ in the rock around the detector produce upward through-going muons in Super–K energetic enough to cross the entire detector. The effective target volume extends outward for many tens of meters into the surrounding rock and increases with the energy of the incoming neutrino, as the higher energy muons resulting from these interactions can travel longer distances to reach the detector. Upward through-going muons are the signature of the highest energy portion of the atmospheric neutrino spectrum observed by Super–K, with the calculated parent neutrino energy spectrum peaking at 100 GeV (Y. Fukuda *et al.*, 1999). The downward going cosmic ray muon rate in Super–K is 3 Hz, making it impossible to distinguish downward-going neutrino-induced muons from this large background, restricting neutrino detection to those events coming from below.

Event reconstruction of a muon is performed using the charge and timing information recorded by the PMT's. Muons are required to have ≥ 7 meters measured path length ($E_\mu >$ 1.6 GeV) in the inner detector, resulting in an effective area for upward through-going muons of ~ 1200 m^2 with a trigger efficiency of $\sim$100%. The arrival direction and time is reconstructed for each muon, with the reconstructed direction of the muon an average of 1.4° from the direction of the parent neutrino. 1416 upward through-muon events have been observed in 1268 live-days from April 1996 to April 2000. More details of the data reduction can be found in Y. Fukuda *et al.* (1998).

The expected background for a WIMP search due to interactions of atmospheric ν's in the rock below the detector is evaluated with Monte Carlo ("MC") simulations using the Bartol atmospheric ν flux (Agrawal *et al.*, 1996), the GRV-94 parton distribution function (Glück *et al.*, 1995), energy loss mechanisms of muons in rock from (Lipari & Stanev, 1991), and a GEANT-based detector simulation.

Analysis of the most recent Super-K atmospheric neutrino data (Kameda, 2001) is consistent with $\nu_\mu \rightarrow \nu_\tau$ oscillations with $\sin^2 2\theta \simeq 1$ and $\Delta m^2 \simeq 2.5 \times 10^{-3}$eV^2. Therefore for evaluating our background we suppress the atmospheric muon neutrino flux using these oscillation parameters. For the Sun, there is an additional background of high energy neutrinos resulting from cosmic ray interactions in the Sun itself, but this is about 3 orders of magnitude less than the observed atmospheric ν flux and hence can be neglected (Seckel *et al.*, 1991). An absolute normalization for the total neutrino flux was obtained by constraining the total number of MC events to be equal to the observed events after taking oscillations into account. In order to compare the expected and observed distributions of upward through-going muon events with respect to the Sun and Galactic Center, each MC event was assigned a random time based on the arrival times of the observed upward through-going muon events. This procedure allowed the angle between each MC muon and any celestial object to be obtained, and thus the distribution of observed and expected upward muons about the three celestial bodies.

4 WIMP Analysis

We searched for a statistically significant excess of observed neutrino-induced upward through-going muons compared to the MC background in cones about the potential source with half angles ranging from 5 to 30 degrees. Smaller WIMP masses result in a larger angular spread of the resulting muons, so different cone angles are used to ensure the capture of 90% of the signal for a wide range of WIMP masses. The different cone angles optimize the signal-to-noise ratio for various potential WIMP masses.

No statistically significant excess was seen in any of the half angle cones. We can therefore calculate the flux limit of excess neutrino-induced muons in each of the cones. The flux limit is given by:

$$\Phi(90\%\,\mathrm{c.l.}) = \frac{N_{\mathcal{P}}(90\%\,\mathrm{c.l.})}{\varepsilon(t) \times A(\Omega) \times T} \quad (1)$$

where $N_{\mathcal{P}}$ is the Poissonian upper limit (90% c.l.) given the number of measured events and expected background due to atmospheric neutrinos (Caso *et al.*, 1998) (taking into account oscillations), and the denominator is the exposure where $A(\Omega)$ is the detector area in the direction of the expected signal (Ω); ε is the detector efficiency ($\approx$ 100% for upward through-going muons); and T is the experimental livetime. Figure 1 shows the flux limits thus obtained for various cone sizes.

Varying the oscillation parameters applied to the background calculation only slightly changes the flux limits close to the celestial objects. The cone with half angle 30° experiences the largest fluctuation, with the flux limits varying as much as

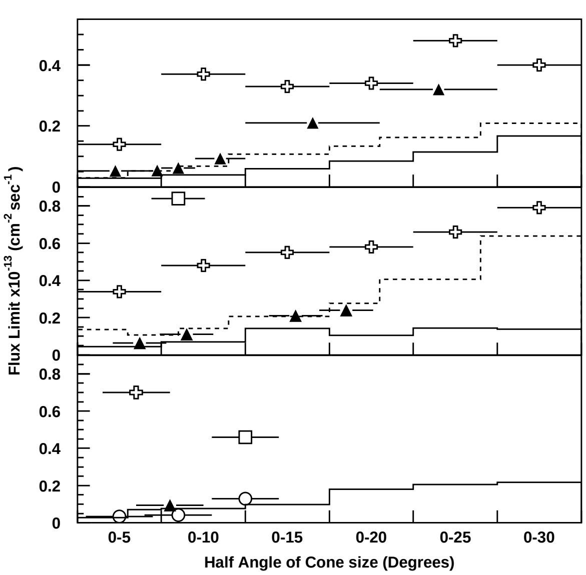

Fig. 1. Comparison of Super-K excess neutrino-induced upward muon flux limits with those from other experiments for the Earth (top), Sun (middle), and Galactic Center (bottom). Super-K limits are solid lines, MACRO dashed lines or circles, Kamiokande crosses, Baksan triangles, and IMB squares. The Y-axis is flux$\times 10^{-13} cm^{-2} s^{-1}$, the X-axis is half-cone angle size in degrees.

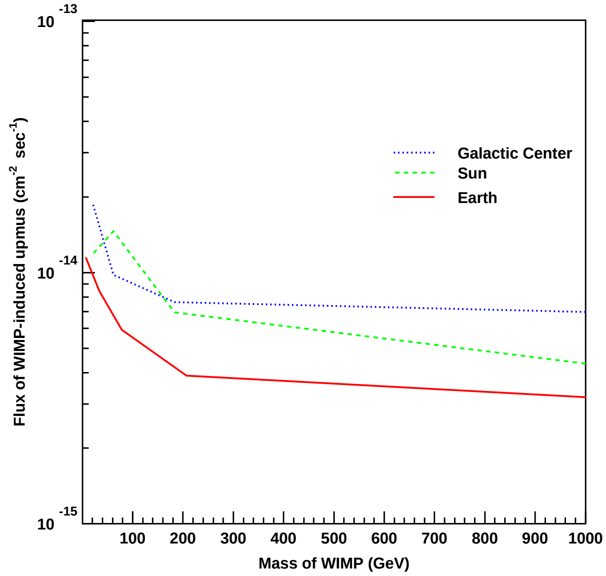

Fig. 2. Super-K WIMP-induced upward-throughgoing muon flux limits from the Earth (solid line); the Sun (dashed line); and the Galactic Center (dotted line) as a function of WIMP mass.

10% for different oscillation parameters in the neighborhood of the Super–K allowed region.

The comparison of Super-K flux limits with previous estimates by other experiments is also shown in Figure 1. All the other experiments have muon energy thresholds around 1 GeV. The WIMP flux limits for the Earth and the Sun by MACRO, Kamiokande, Baksan, and IMB are given in (M. Ambrosio *et al.*, 1999; M. Mori *et al.*, 1991; O.V. Suvorova, 1999; J.M. LoSecco *et al.*, 1986), and the WIMP flux limits for the Galactic Center by the above detectors are given in (M. Ambrosio *et al.*, 2001; Y. Oyama *et al.*, 1989; M.M. Boliev *et al.*, 1995; R. Svoboda *et al.*, 1987).

Once WIMPs are gravitationally captured in the Sun and the Earth they settle into the core with an isothermal distribution equal to the core temperature of the Sun or the Earth (Jungman *et al.*, 1996). Although both the Sun and the Galactic Center are effectively point sources of energetic neutrinos resulting from WIMP annihilations, the Earth is not. Furthermore, muons scatter from the incoming direction of their parent neutrino due to the kinematics of the initial interaction and multiple coulomb scattering in the rock below the detector.

The Kamiokande collaboration (M. Mori *et al.*, 1991) has calculated the angular windows for Sun and Earth which contain 90% of the signal for various WIMP masses. Using these windows, 90% confidence level flux limits can be converted to a function of WIMP mass using the cones which collect 90% of expected signal for any given mass. These flux limits as a function of WIMP mass are shown in Figure 2 for the Earth and Sun.

5 Indirect vs. Direct Searches

In contrast to the indirect WIMP search described above, direct-detection experiments seek to observe the $\mathcal{O}$(keV) energy deposited in a low-background detector when a WIMP elastically scatters from a nucleus therein. However, rates for both techniques depend primarily upon the WIMP nucleon cross-section, either to collide with a nucleus in the detector, or in a celestial body (and drop below the excape velocity). The two additional uncertainties which arise in indirect searches for WIMPs relate to the second moment of the neutrino energy spectrum and the suppression of annihilation of WIMPs relative to capture. Thus, using extreme cases for the above two factors it is possible to compare the sensitivities of direct and indirect experiments. Kamionkowski *et al.* (1995) calculate the maximum and minimum values of the ratio of direct to indirect detection rates for WIMPs with both scalar and axial vector interactions. They find that the event rate in a 1 kg of Germanium detector is equivalent to that in $10^4 - 10^6$ m^2 of upward muon detector.

The DAMA direct-detection experiment reports a detection of WIMPs based on the annual modulation of their event rate. Their cumulative analysis is consistent with the possible presence of WIMP at the 4σ confidence level, with the best fit values being : M_w = 52 GeV and $\sigma_p = 7.2 \times 10^{-6}$ pb (Bernabei, 2000). The CDMS direct-detection experiment, however, does not see any WIMP signal. CDMS data give limits on the spin-independent WIMP-nucleon elastic-scattering

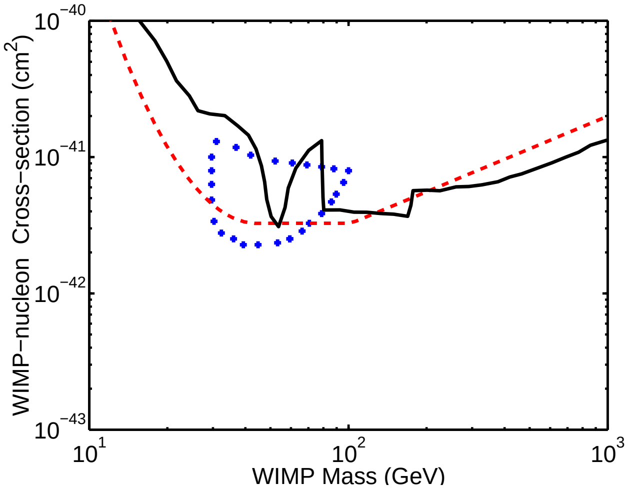

Fig. 3. Super-K 90% c.l. exclusion region in WIMP cross section vs. WIMP mass parameter space (above solid line), compared to the DAMA 3σ allowed region (inside crosses) and the CDMS 90% c.l. excluded region (above dashed line).

cross-section that exclude parameter space above a WIMP mass of 10 GeV c^{-2}. This excludes the entire 3σ allowed region for the WIMP signal reported by the DAMA experiment at > 84% c.l. (R. Abusaidi *et al.*, 2000).

Using the results of Kamionkowski *et al.* (1995) it is possible to obtain limits on WIMP-nucleon spin-independent cross-section from the Super-K flux limits and compare them with the results of the DAMA and CDMS direct-detection experiments. The combined WIMP flux limits from the Sun and the Earth as a function of WIMP mass were calculated. Since the goal is to calculate an *upper limit* on WIMP-nucleon cross-section, the most conservative direct/indirect ratio in Kamionkowski *et al.* (1995) was used with the Super–K flux limits to calculate the limit on WIMP nucleon cross-section as a function of WIMP mass. The Super-K upper limits on WIMP nucleon cross-section are shown in Figure 3, along with the CDMS upper limits and the DAMA best fit region. These limits rule out a signification portion of the WIMP parameter space favored by the DAMA experiment.

6 Conclusions

An indirect search for dark matter was performed using 1416 neutrino-induced upward through-going muon events observed by the Super-K detector corresponding to 1268 days of livetime. High energy ν can be produced from WIMP annihilation in the Sun, the Earth, and the Galactic Center. We looked for an excess of upward muons over the atmospheric neutrino background coming from near those bodies. No statistically significant excess was seen.

The lack of excess neutrinos allows flux limits to be obtained for various cone angles around these potential sources and compared with previous measurements from other detectors. For the Sun and the Earth these flux limits can be calculated as a function of the WIMP mass. A comparison of these results with the direct-detection results from CDMS and DAMA shows a similar sensitivity to a potential WIMP signal over a wide range of parameter space.

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